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EATS AND APATS TELEMETRY ANTENNA PERFORMANCE COMPARISON IN A BALLISTIC MISSILE TERMINAL AREA SUPPORT ROLE

By: J. F. CLINE E. G. BLACKWELL

Prepared for:

THE STRATEGIC SYSTEMS TEST SUPPORT STUDY AD HOC COMMITTEE
THROUGH THE
U.S. ARMY BALLISTIC MISSILE DEFENSE SYSTEMS COMMAND
BMDSC-CRR
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(dual-polarization), and the other as an upgrade with dual-polarization and increased elevation scan angle commensurate with the APATS specification. Study findings indicate that the second EATS upgrade option results in telemetry collection performance essentially equal to that of the APATS. RV telemetry blackout (SNR < 13 dB) for the EATS upgraded antenna lasted slightly longer than the blackout of the APATS antenna. Blackout is relatively unimportant in the MK-4 application, but may be more consequential in the MK-12 application. The minimum EATS antenna upgrade (dual-polarization) does not perform well for ballistic missile telemetry support, so that the full upgrade is indicated for the EATS telemetry antenna in this mission role.

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I INTRODUCTION AND SUMMARY

A. Study Purpose

The Extended Area Test System (EATS) telemetry (TM) antenna has been designed for installation on P-3A Orion aircraft to receive signals from surface and airborne TM transmitters located within the offshore extended area of the Pacific Missile Range in Southern California. The ARIA Phased Array Telemetry System (APATS) antenna, for which a performance specification* has been written and design phase contractor proposals have been evaluated, is to be installed on an EC135N or 707-320C aircraft for use in the broad ocean area to receive signals from TM transmitters placed on up to four instrumented objects, such as Trident and MX reentry vehicles. SRI has been asked by the Strategic Systems Test Support Study (SSTSS) ad hoc committee to evaluate the potential effectiveness of two postulated modified forms of the EATS antenna on P-3B aircraft (upgraded from P-3A) as possible substitutes for the APATS antenna in the Trident/MX application. This report presents the results of this analysis and compares the performance of the EATS antenna upgrade options with a postulated APATS antenna. This work was performed as a separate task under the SRI SSTSS contract through the U.S. Army BMDSCOM, Huntsville, Alabama.

Prior to this comparative analysis by SRI, other analyses were performed by Pacific Missile Test Center (PMTC) to estimate the capability of the EATS antenna to receive telemetry data from a reentry vehicle (RV) during reentry. Also, the APATS specification had been derived by MITRE to satisfy the telemetry collection needs for the ARIA, principally in an ICBM terminal area test support role. However, these previous EATS and

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*"System Specification for APATS," SS-OCD-429080, Code Ident 50464 (1 October 1980).

APATS performance estimates were not made with the same set of assumptions and conditions and therefore did not lend themselves to valid comparison. Moreover, the aircraft standoff and test support criteria have since been better defined by SAMTO/DOS, and targeting lay-down geometrics for multiple RVs have been clarified by the users. Thus, an objective of SRI's analysis was to evaluate several telemetry antenna configurations against a common set of support requirements that reflects a better understanding of Air Force and Navy support needs.

B. General Description: EATS and APATS Antennas

The EATS antenna is a flat array build into a forward extension of the tail fin of the P-3A aircraft. It is a two-sided array, operating only one side (port or starboard) at a time, the choice being made by a switch. Each side has a physical area of about 7 m^2 and is designed to receive right-hand circular polarization (RHCP) but not left-hand circular polarization (LHCP), using five simultaneous independently scanning beams. The beams have a wide azimuth scan capability, but their elevation scan capability is limited. In comparison, the APATS will be one sided only, will have only four simultaneous independently scanning beams, and will receive both RHCP and LHCP with pre- and post-detection combining capability. The APATS beams will have a large scan capability in elevation as well as azimuth. The location and form of the APATS antenna have not been completely determined. It probably will be located on the right side of the fuselage, forward of the wing. It may be a conformal array or it may be a flat array faired into the fuselage.

The first postulated modified form of the EATS antenna, called Mod-1 in this report, differs from the original only by the fact that it meets the APATS dual polarization requirements. It does not meet the APATS scan or sensitivity requirements. The second form, called Mod-2, meets both the dual polarization and scan requirements of the APATS. However, it is no larger than the original and therefore does not meet the APATS sensitivity requirement. A third form of the EATS antenna, called Mod-3, was employed in this study to simulate the yet-to-be-designed

APATS antenna for comparison purposes; Mod-3 is simply a Mod-2 antenna that is enlarged sufficiently to meet the APATS sensitivity requirement at maximum off-axis scan. In the illustrations and tables in this report it is referred to as the "APATS equivalent" antenna, and it is assumed to be installed on the side of the fuselage of an EC135N or 707-320C type of aircraft, forward of the wing, and boresighted 15° above horizontal.

Because of lower internal losses, the final APATS antenna may be somewhat smaller physically than the EATS Mod-3, since it is assumed that the Mod-3 retains the same aperture efficiency and system noise temperature as the original EATS antenna. However, this cannot be known with certainty until the APATS antenna has been designed. Also, the APATS antenna may be smaller because the APATS specification gives the contractor the option to make it smaller under certain conditions. Specifically, in the sections of the APATS specification for field of view (3.2.1.4.6), sensitivity (3.2.1.4.8), and aperture (3.2.1.4.9), the following parenthetical caveat is added: "TBD, the contractor may modify these specific numerical requirements as a result of system trade-off studies involving sensitivity, field of view, aperture, and other parameters." In the study reported here no attempt was made to anticipate the results of such trade-off studies. Instead, the numerical requirements of the specification for field of view and sensitivity are assumed to apply. The aperture specification is discussed, but it is not assumed to hold strictly, as long as the sensitivity requirement is met.

C. Study Procedure and Summary of Results

In the analysis, the Mod-1, Mod-2, and APATS equivalent (Mod-3) antennas were exercised against several Trident MK-4 and MX MK-12 RV trajectories, using RV antenna patterns and plasma loss curves given in the APATS data-collection environment specification, and using the reception criteria of 13 dB signal-to-noise ratio (SNR) for a bandwidth of 1.5 MHz, given in the APATS sensitivity specification. The results are summarized in Table 1.

Table 1

SUMMARY OF RESULTS

Antenna Type	Trident MK-4	MX MK-12A
EATS Mod-1 (Dual-Polarization)	Suffers excessive high altitude blackouts with level aircraft. Banking aircraft helps high altitude, but loses data to impact. Not suggested for BOA TM support.	Permits more blackouts than other mods for both Case 2 and 3. May avoid blackout in Case 2 if aircraft is banked.
EATS Mod-2 (Mod-1 plus increased elevation scan)	*Shortens blackout periods--* acceptable with MK-4 delay link. Nearly equivalent to APATS.	*No blackout in Case 2 trajectory.* Brief blackout likely in Case 3. Nearly equivalent to APATS.
APATS Equivalent* (Enlarged Mod-2 EATS, called Mod-3)	Slightly shorter blackout, still needs MK-4 delay link to recover all data.+	No blackout in Case 2 trajectory. Very brief blackout likely in Case 3.

*The array form and the system temperature that can be achieved for the APATS are unknown at present.

+Recording and playback are planned for the MK-4, but not for the MK-12A.

Against the Trident MK-4, the Mod-1 EATS antenna will suffer blackouts during part of each trajectory. High RV altitude blackout is noticeably worse than for other mods. Banking the aircraft during reentry plasma peaks will shorten these high altitude blackout periods, but at the expense of failing to obtain signals of sufficient strength post-blackout when MK-4 delayed-link retransmission is being received prior to impact. This operating procedure also may be impractical for multiple RV impacts. Against the MX MK-12, the EATS Mod-1 antenna is not recommended. It will suffer excessive blackouts at either high or low RV altitudes with both medium and low plasma loss (Case 2 and Case 3, respectively) trajectory cases* (the only cases for which plasma loss data are available), although it may be able to handle Case 2 if the aircraft is banked.† In general, the TM signal strength received from the AF MK-12A RV is 15 to 30 dB greater than that for the Navy MK-4, but, since the MK-12A does not employ a TM delay retransmission, blackout has a more serious effect in terms of loss of data.

The Mod-2 EATS antenna will shorten the blackout periods of the MK-4 to an acceptable degree, but will not eliminate them. Against the MK-12, it will handle Case 2, but it probably will lose Case 3 briefly near plasma peak, as will APATS.

The APATS equivalent antenna (Mod-3 EATS) will shorten the MK-4 blackouts still further but will not completely eliminate them. It will handle the MK-12 Case 2 trajectory, but, as with Mod 2, it still may lose Case 3 briefly near plasma peak, depending on the geometry and the number of RVs that must be tracked at one time.

In cases (e.g., Navy MK-4) in which the RVs have on-board recording and playback capability, the blackout effects can be circumvented. Playback and transmission would occur during the time available after blackout

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*The high plasma loss case (1) for the MK-12 was not made available for this study.

†However, discussions with the 4950th TW/FEE indicate that maintaining a controlled aircraft bank is not practical.

and before impact. The Mod-2 antenna, in general, will be able to provide from 30% to 50% more data reception time than the Mod-1. The APATS equivalent (Mod-3) antenna, however, will be able to provide in general only 5% to 10% more time than will the Mod-2.

In summary, it appears that an EATS antenna, provided it is upgraded to Mod-2 capability, will perform almost as well as the full APATS equivalent.

During this analysis, a question arose regarding the minimum antenna angular coverage and figure of merit (G/T) that would be required as a function of elevation coverage. The last topic in this report briefly addresses this requirement by consolidating the G/T required for the more stressing RV trajectory cases investigated. This supplemental analysis shows the theoretical maximum G/T required, as a function of elevation angle, if all RV TM signal blackout were to be avoided. These data show the impracticality of eliminating blackout for all RV cases because of the large antenna sized implied. They also show that a respectable G/T (perhaps at least as good as the current ARIA TM dish) needs to be maintained at elevation angles up to about 40^{o} when aircraft roll margins are included.

II EATS AND APATS ANTENNA CHARACTERISTICS

A. EATS Antenna

The EATS TM antenna data were obtained from Design Plan DP-500.* The data of principal interest in the present study are summarized in Table 2. The antenna has two flat array faces, port and starboard, only one of which can be used at one time. The antenna is mounted vertically in a forward extension of the tail fin of the P-3A aircraft, and the boresight of each face of the antenna array is horizontal. Each face has a total of 1120 elements, arranged in 56 columns and 20 rows, with a total area of 7.2 m^2. Each face can generate five simultaneous independently scanning beams.

The azimuth and elevation patterns of the beams are shown in Figures 1 and 2, which were redrawn from DP-500 with envelope curves added. It can be seen that $(\cos A)^{1.25}$ is a practical envelope for the azimuth beams. There are 54 main azimuth beam positions, but only 4 main elevation beam positions. Three of the elevation beam positions are intended to provide maximum gain slightly below horizontal while correcting for normal amounts of inadvertent aircraft roll. The fourth elevation beam has a wide high angle coverage with relatively lower gain.. The curve $0.32 (\cos E)^7$ is seen to be an approximate fit to this beam. This lower gain at higher elevation angles was sufficient for the EATS application, in which all TM sources at high angles were located in airborne vehicles at relatively short ranges (e.g., overflying aircraft), but it is inadequate for many ICBM applications.

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*Design Plan DP-500", Airborne Instrumentation Station, Contract N00123-76-C-0126, General Dynamics Electronics Division, San Diego, CA (16 May 1979).

Table 2

EATS TM ANTENNA CHARACTERISTICS

Type	Flat array, two faces: only one face can be used at one time
Mounting	Vertical, above fuselage, forward of tail
Physical area	7.2 m^2 each face
Number of antenna elements	1120 (20 rows, 56 columns)
Number of beams	5 per face
Azimuth scan	Plus to minus 66° 54 positions*
Elevation scan	-7.5° to +2.5°, 3 main positions*
Tracking method	Sequential lobing
Polarization	Right-hand circular (only)
Boresight aperture	2.9 m^2
System noise temperature	415 K
G/T dB/K	6.9†

*Many intermediate positions can be obtained by signal combination in the pre-detection RF circuitry.

†At band center (2250 MHz).

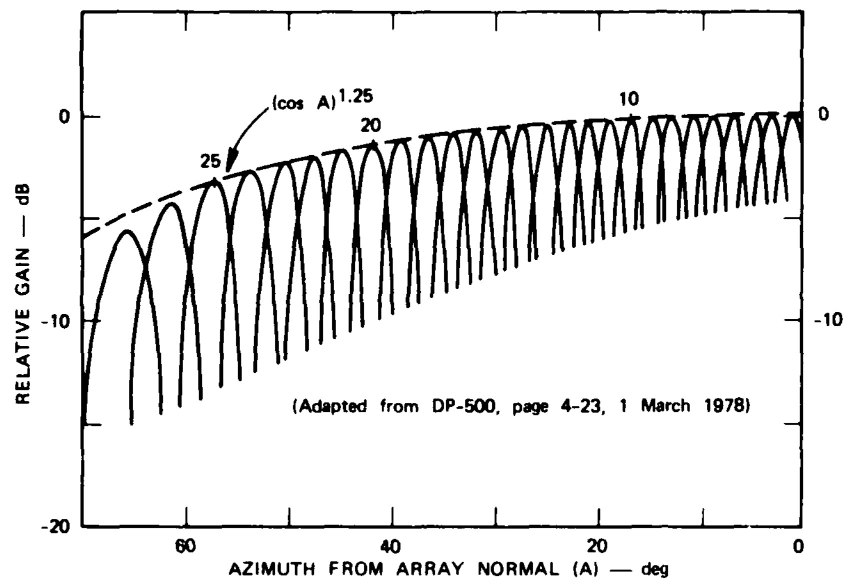

FIGURE 1 AZIMUTH PATTERN OF UNMODIFIED EATS ANTENNA, WITH EMPIRICAL 1.25 POWER ENVELOPE (dotted line) ADDED FOR REFERENCE

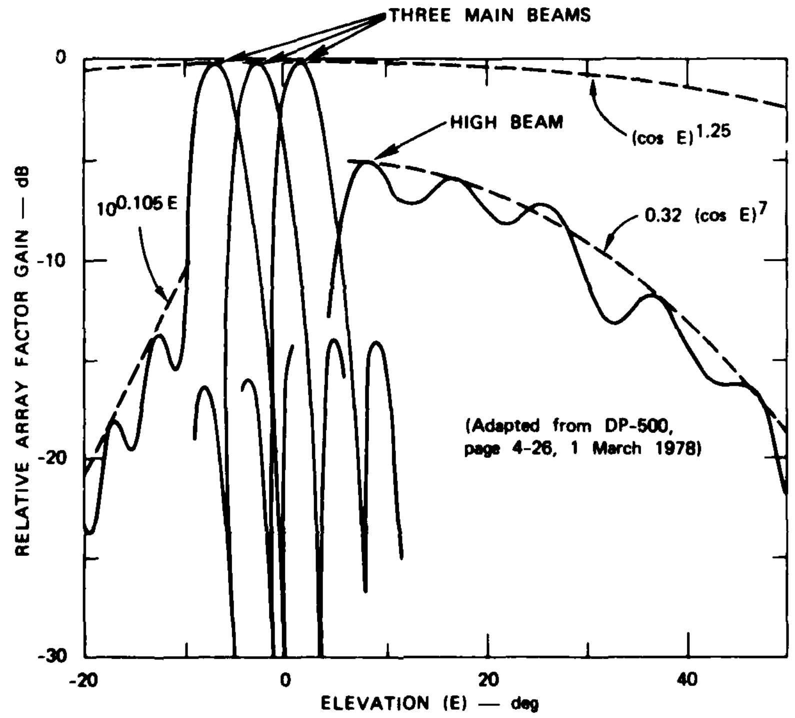

FIGURE 2 ELEVATION PATTERN OF UNMODIFIED EATS ANTENNA, WITH EMPIRICAL ENVELOPES (dotted curves) ADDED FOR REFERENCE

The method of beam positioning is to select, by means of switches, among the multiple output ports of special elevation and azimuth lenses, as illustrated in Figure 3. These are printed circuit lenses of the Rotman type. This provides 216 primary positions (54 in azimuth times 4 in elevation). After primary position selection, five-way beam splitting, further filtering, and amplification, a fine steering unit permits a fine positioning of each beam between adjacent main positions, making a total of several thousand possible positions for each of the five beams.

Each antenna element has a loss of 0.9 dB. Each column of 20 elements is connected through cables to its elevation lens. The average loss in these cables is 0.4 dB, and the lens loss is 0.8 dB. The output ports of each elevation lens are connected through other cables to the port/starboard switch. The average loss in these cables also is 0.4 dB, and the switch loss is 0.1 dB. Each output port of the switch is connected through an RFI filter, having a loss of 0.3 dB, to the first RF amplifier in the chain. The total loss before first amplification is the sum of the above losses, or 2.9 dB. Although post-amplification losses (azimuth lens, beam splitting, switching) contribute further to the system loss, this 2.9 dB loss is the principal explanation for the fact that the antenna boresight effective aperture is only 2.9 m^2, compared with the physical array area of 7.2 m^2. A more efficient design would have been to provide each antenna element with its own integral RFI filter and amplifier, although this would increase the total cost of the array and might affect its reliability.

The tracking method employed is sequential lobing. Automatic amplitude comparison of sequential beams, surrounding the direction of each arriving signal, is employed to direct the beams.

The boresight gain of the antenna is 33.0, 33.1, and 33.2 dB at the lower edge, center, and upper edge, respectively, in the 2.2-to-2.3 GHz band. The manufacturer gives the system noise temperature as 415 K. The corresponding values of boresight G/T are 6.8, 6.9, and 7.0 dB/K.

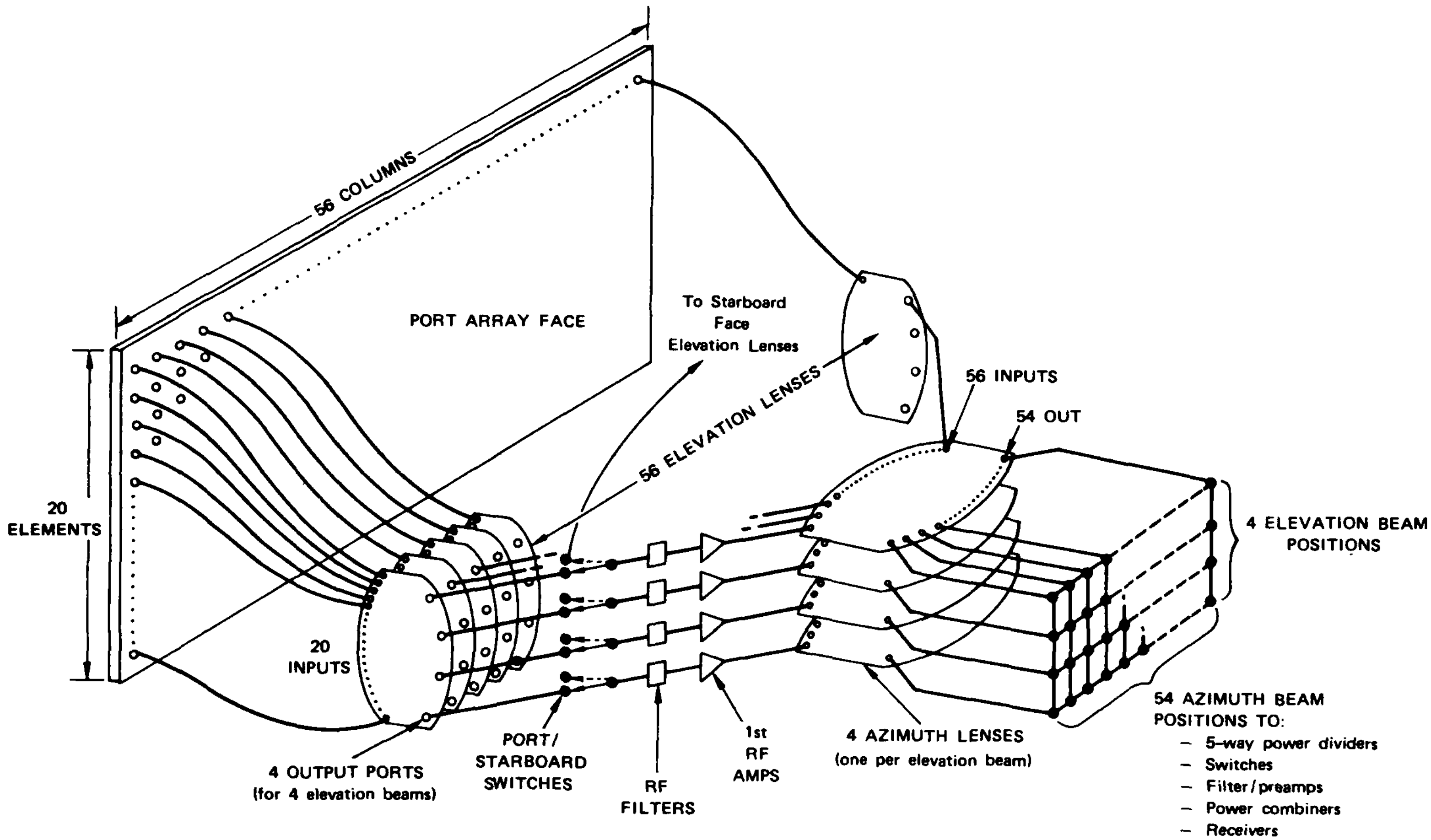

FIGURE 3 CONCEPTUAL ARRANGEMENT OF EATS ANTENNA BEAM-FORMING NETWORK USING ROTMAN LENSES

B. APATS Antenna

1. Requirements

The numerical requirements in the APATS specification that were of primary interest in the study are summarized in Table 3. The field strength of 6.7 μV/m corresponds to a normal incident power density (D_p) equal to 1.19×10^{-13} W/m^2 (-129.2 dBW/m^2). The required aperture is given by

$$A = kTBR_{sn}/D_p \quad , \tag{1}$$

in which $k = 1.38 \times 10^{-23}$ J/K (joules per kelvin), T is the noise temperature in kelvins, D_p has the value given above in W/m^2, and, from Table 3, $B = 1.5 \times 10^6$ MHz and $R_{sn} = 20$. Since the APATS has not yet been designed, an estimate has to be made for T. For the present, it is estimated that the APATS system temperature will be 350 K, which is 65 K lower than that given for the EATS system by the manufacturer. This is reasonable if it is assumed the APATS design will be somewhat more advanced than that of the EATS because of improvements in the state of the art.* The sky temperature in the direction of the RVs emerging from the plasma region probably will be 15 K or less in many cases; if this value is added to the above 350 K, the result is T = 365 K. The aperture given by Eq. (1) then is found to be 1.27 m^2. This aperture must be attained even in the maximum off-axis scan direction. If the antenna is a flat array, the ratio of the off-axis aperture to the boresight (on-axis or normal) aperture can be estimated from

$$n = [(\cos a)\ (\cos b)]^{1.25} \quad , \tag{2}$$

in which a and b are the angles off-axis in the principal planes. If the array is tilted so that its boresight is 15° above horizontal, as

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*It may also be possible to improve the EATS telemetry system noise figure somewhat if an upgrade design is pursued.

Table 3

APATS ANTENNA PERFORMANCE REQUIREMENTS

Number of Beams	Four, Independently Steerable	Notes
Polarization	Right- and left-hand circular, delivered to separate output ports (two ports per beam), with pre- and post-detection combining capability	
Angular coverage	Azimuth -60° to $+60^{\circ}$ Elevation -15° to $+45^{\circ}$	1
Sensitivity (one second average with polarization aligned)	Signal/noise ratio 20 (13 dB) Bandwidth 1.5 MHz Field 6.7 μV/m	1,2
Aperture	4 m^2	1,3

1. Numerical requirements may be modified if warranted by results of contractor trade-off studies.

2. Corresponds to G/T = 3.9 dB at band center and scan limit.

3. Corresponds to G/T = 8.4 dB if T = 415 K, which is the EATS system temperature.

will be supposed here, the required angular coverage can be obtained if $a = 30^{\circ}$ and $b = 60^{\circ}$. This gives $n = 0.35$. The boresight aperture, A_n, is then found by dividing the above 1.27 m^2 by 0.35. The result is $A_n = 3.6\ m^2$, which may be compared with the value of 4 m^2 given in the APATS specification (but not employed in this study).

The ratio of the boresight aperture to the physical area of the array is called the aperture efficiency. This may vary, depending on the design details (it is approximately 0.4 for the EATS array). In the case of the APATS array, because of its location, it may be possible to have shorter cable runs from the antenna elements to the initial amplifiers and thus attain a higher aperture efficiency. If 0.6 is used as an estimate, the physical area of the array would be 3.6m^2 divided by 0.6, or 6 m^2.

2. Possible Configurations

Two possible forms of an APATS array, located on the side of the fuselage, are the flat array discussed above and a conformal array. The area of the flat array was computed above as 6 m^2. The area of the conformal array would have to be larger, depending on how tall it is, measured around the fuselage surface. If this dimension is 4 m, for example, and if the center is 15° above horizontal, the array would extend from about 75° above horizontal to about 45° below horizontal. With this amount of curvature, the physical area probably would have to be increased to about 10 m^2, so that the width would have to be about 2.5 m^2. The flat array, in comparison, might be 1.5-m tall and 4-m wide. The two arrays, with these approximate sizes, are sketched on an outline of a photograph of an APATS aircraft in Figure 4.

The gain of the flat array would vary from about 29.5 to 34 dB, depending on the scan angle. The azimuth beamwidth would vary from about 2.5° to 5° and the elevation beamwidth would vary from about 6.5° to 7.5°. The figure of merit, G/T, would vary from about 4 to 8.6 dB/K. The gain of the conformal array, in comparison, would have the same maximum scan value of 29.5 dB, and the G/T at maximum scan would still be about 4 dB/K, but the boresight gain and G/T might be 0.5 or 1 dB lower than those of the flat array, depending on the detailed design and

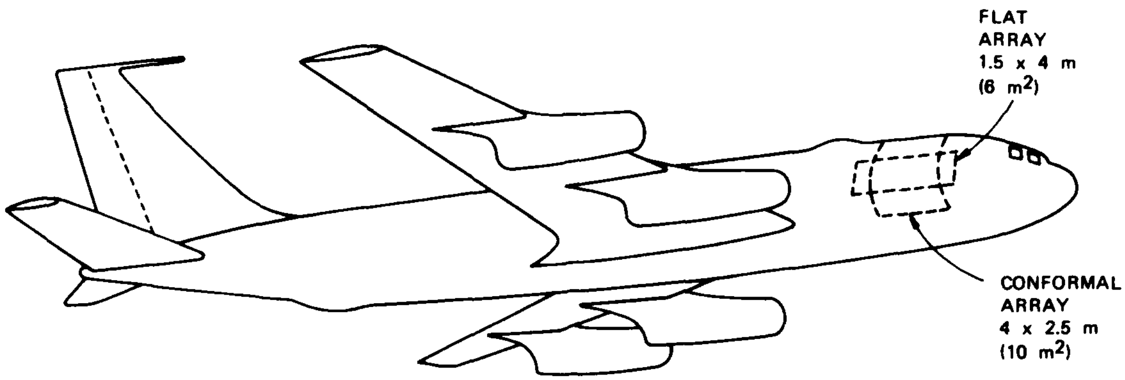


FIGURE 4 TWO POSSIBLE APATS ARRAY LOCATIONS

whether or not all of the antenna elements are used at the maximum high- or low-elevation scan. The beam would be more pencil-shaped than that of the flat array and would have a half power beam width varying from about 4° to 7°.

C. Comparison of EATS and APATS Antenna Characteristics

The characteristics of the original EATS, Mod-1, Mod-2, and APATS equivalent (Mod-3 EATS) antennas are compared in Table 4. The original antenna receives RHCP, but not LHCP, while the other three receive both RHCP and LHCP with pre- and post-detection combining capability. The elevation scan in both the original and in Mod-1 is -7.5° to $+2.5^{\circ}$, with higher angles covered by a separate wide-angle beam with lower gain. In Mod-2 and APATS, the elevation scan coverage is -15° to $+45^{\circ}$. In the APATS equivalent case, this is obtained by mounting the antenna with the boresight tilted 15° above horizontal and scanning 30° above and below boresight. Figure 5 illustrates the approximate G/T elevation profile relationships for the three antenna cases investigated.

The physical area of the original, Mod-1, and Mod-2 antennas is 7.2 m^2, while that of the APATS equivalent antenna is 10.6 m^2, computed on the basis of the assumed aperture efficiency of 0.4 and temperature of 415 K, both characteristic of the existing EATS design. By using

Table 4

ANTENNA COMPARISON

Characteristic	EATS Original	EATS Mod-1	EATS Mod-2	APATS Equivalent (EATS Mod-3)
Polarization	RHCP only	RHCP and LHCP with pre- and post-detection combining	Same	Same
Elevation scan coverage	-7.5 To +2.5	-7.5 To +2.5	-15 To +45	-15 To +45
Physical area m^2	7.2	7.2	7.2	10.6 (1)
Boresight aperture, m^2	2.9	2.9	2.9	4.3 (2)
Aperture efficiency	0.4	0.4	0.4	0.4 (1)
System noise temperature, ^{o}K	415	415	415	415 (3)
Sensitivity at 45-60 scan relative to APATS specification, dB	-19.4	-16.4	-2.8	0
Boresight G/T for random polarization, dB/K	3.9	6.9	6.9	8.6 (3)

(1) In final APATS design, efficiency may be higher and area therefore may be smaller.

(2) If final APATS design is a curved array, boresight gain and aperture will be smaller for same maximum-scan gain.

(3) If T is lower in final APATS design, G will be lower in the same proportion.

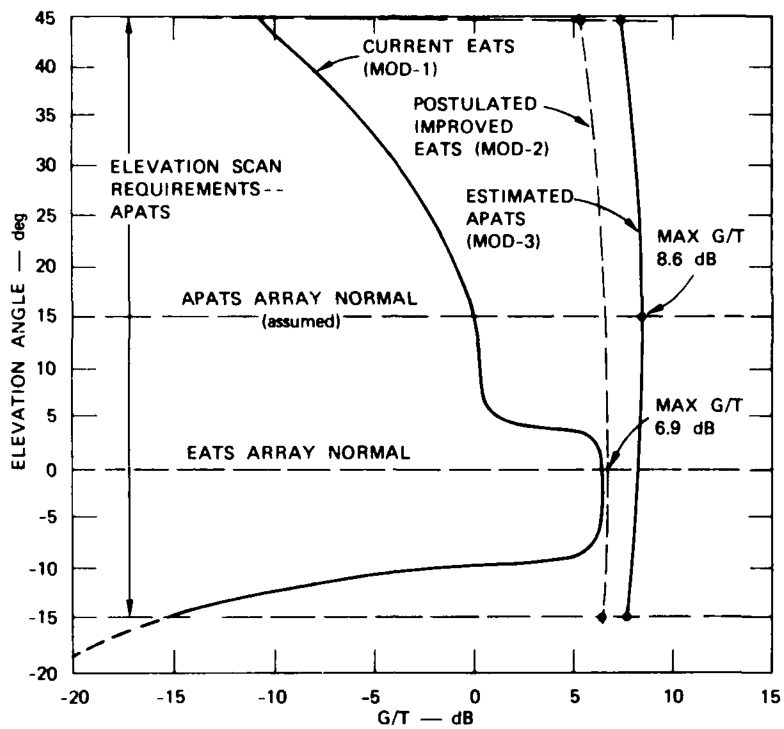


FIGURE 5 ELEVATION SCAN G/T PROFILES FOR EATS/APATS CASES

Eq. (1) with $k = 1.38 \times 10^{-23}$ J/K, T = 430 K (415-K system temperature plus 15-K sky temperature), $B = 1.5 \times 10^{6}$ Hz, $R_{sn} = 20$, and $D_p = 1.19 \times 10^{-13}$ W/m^2, the required aperture, A, is found to be 1.5 m^2. When this is divided by the value of n equal to 0.35, given by Equation (2) with a = 30^o and b = 45^o, the boresight aperture, A_n, is found to be 4.3 m^2. When this is divided by the assumed aperture efficiency of 0.4, the above value of 10.6 m^2 for the physical area is obtained. (As noted in the preceding section, the system temperature of the final APATS design may be lower than 415 K, which would reduce both A and A_n, which is turn would reduce the physical area. Also, the aperture efficiency of the final APATS may be higher than 0.4, which would reduce the physical area even further.)

The sensitivity at maximum scan, relative to the APATS, is -2.8 dB for the Mod-2 EATS antenna, partly because of the smaller antenna size and partly because of the greater off-axis vertical scan required in the Mod-2 to reach $+45^{o}$ in elevation. Because of the weak high-angle beam of the Mod-1 antenna, its sensitivity is -13.6 dB relative to that of the Mod-2, which brings its gain relative to that of the APATS down to -16.4 dB. The gain of the original antenna is 3 dB below that value, or -19.4 dB, because of the RHCP polarization limitation.

The boresight G/T at band center was given in the previous section as 6.9 dB/K for the original EATS antenna working against a RHCP source. Against a random RHCP/LHCP source, it drops 3 dB to an average of 3.9 dB. Because of the dual polarization capability of the Mod-1 and Mod-2 antennas, which have the same physical area as the original, this 3 dB is restored and G/T = 6.9 dB/K. The normal aperture of the APATS (Mod-3) is 4.3 m^2, as compared with 2.9 m^2, which increases G by 1.7 dB, giving G/T = 8.6 dB/K.

III ANALYSIS FACTORS

Several related parameters that vary during a reentry event required definition for this analysis. These factors are illustrated in Figure 6 in terms of how they relate to the geometric aspects of the problem. These factors are:

- The test support position of the aircraft relative to the trajectory ground trace.
- The plasma loss versus altitude and reentry conditions for Air Force (MK-12) and Navy (MK-4) reentry vehicles.
- The respective RV telemetry antenna gains versus aspect angle.
- The aircraft telemetry antenna gain as a function of elevation and azimuth "look" angles.

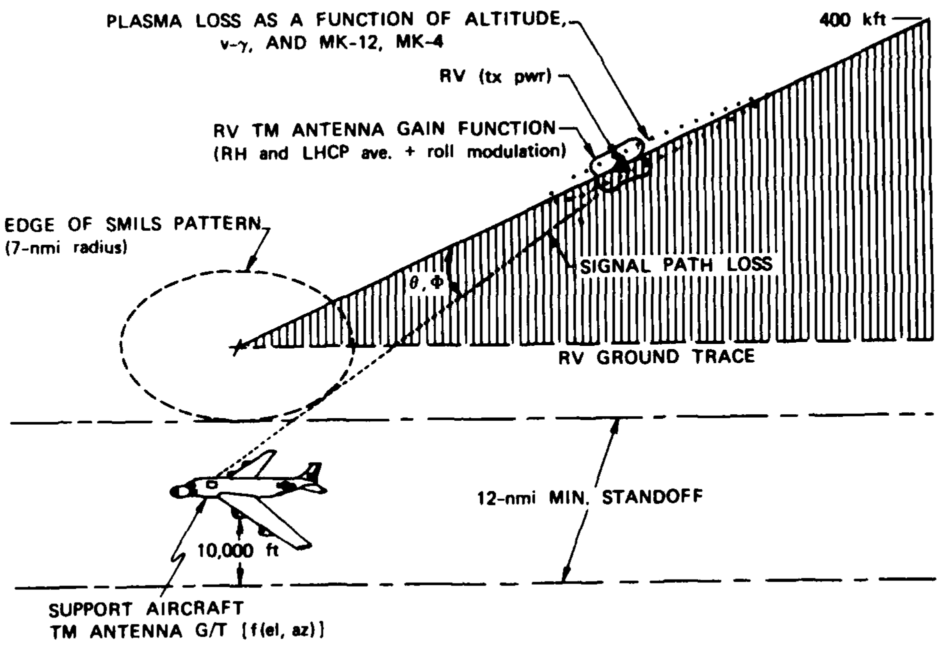


FIGURE 6 GENERIC SUPPORT GEOMETRY

The following section describes these parametric relations.

A. Aircraft Altitude and Standoff Distance

For this study, it was assumed that all RVs will impact within a circular SMILS* pattern having a radius of 7 nmi, while the test support aircraft will be stationed 19 nmi (35,188 m) from the center of the circle and cross-range from the trajectory ground traces. This support geometry is illustrated in Figure 7 and is consistent with the intent

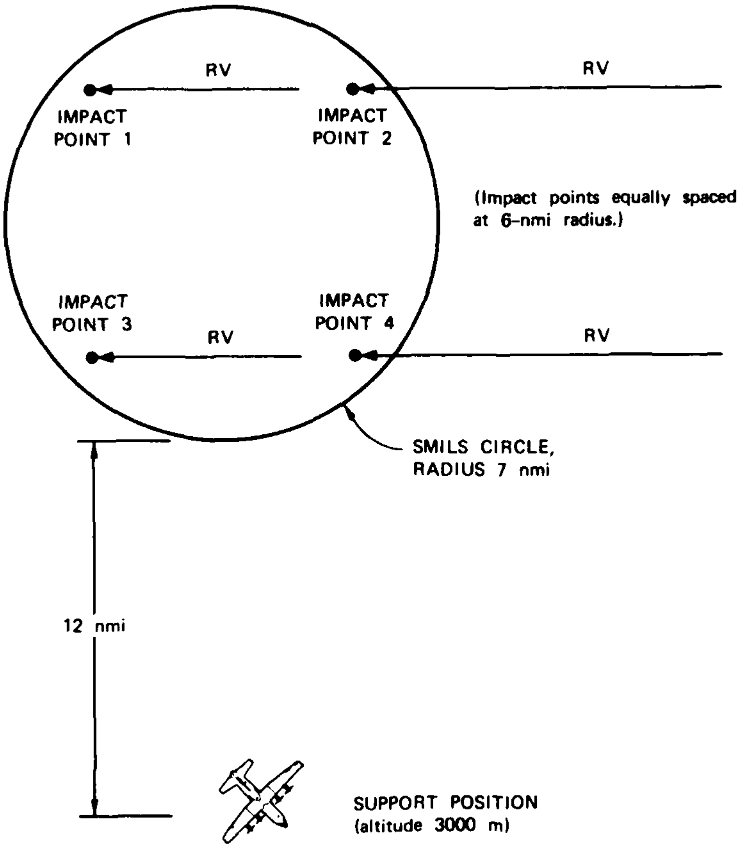


FIGURE 7 ASSUMED IMPACT PATTERN AND INSTRUMENTATION SUPPORT POSITION

*Sonobuoy Missile Impact Location System.

of Attachment 1 (aircraft standoff requirements) of the memo to SAMSO/CA from Lt. R. Hassan, dated 2 December 1980. Although Western Space and Missile Center (WSMC) Range Safety indicates that 5 nmi cross-range standoff is acceptable, this position would increase the angular field of view (FOV) required of the telemetry antennas. The impact points numbered 1 through 4, used in several examples below, are equally spaced at a distance of 6 nmi from the center of the SMILS pattern.

For this analysis, the altitude of the aircraft was taken as 3000 m (9843 ft). While this choice was not the result of a detailed trade-off study, it appeared to be a good choice from the standpoint of multipath interference, maintaining line-of-sight to the SMILS sonobuoy array, and being in relatively clear air for photographic purposes. As the RVs emerge from the plasma region, the angle between the direct and reflected rays arriving at the aircraft antenna may be 20° or more, but, as the RVs approach impact, this angle approaches zero, which means the receiving antenna beam can no longer provide angular discrimination between direct and reflected rays. Some discrimination against the reflected signal is provided naturally if the surface reflection coefficient is sufficiently low. In general, this will be the case in the higher sea states. If the water is smooth, the coefficient varies with both the angle of reflection and the polarization, as shown in Figure 8. If the RHCP and LHCP combination is adjusted in the receiving or recorder playback circuits to cancel sensitivity to horizontal polarization, the remaining vertical polarization will be least susceptible to multipath interference when the angle of reflection is between about 3° and 12°. With the aircraft altitude of 3000 m and the standoff distance chosen here, the average reflection angle for various points within the SMILS circle usually will fall within this range. Because multipath effects depend on wind direction, sea state, and polarization, and because they are usually unimportant when the RV is in the plasma loss region, they are not modeled in the computations used in this study. (Because of the multipath problem there may be merit in specifying an APATS ability to suppress horizontal polarization, even though this ability already may be implied in the requirement to combine RHCP and LHCP.)

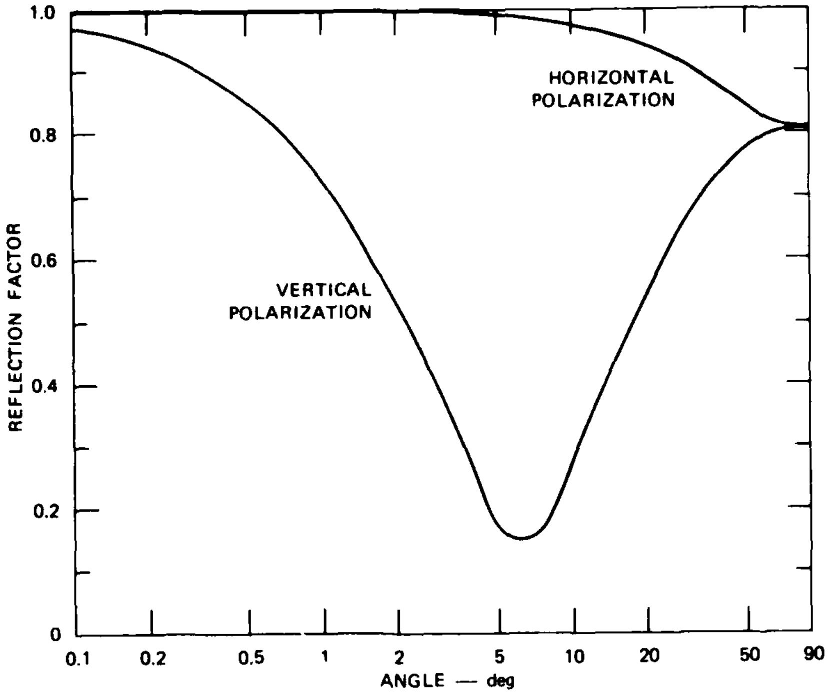


FIGURE 8 THEORETICAL REFLECTION FACTOR FOR SMOOTH SEA WATER AT 2250 MHz

B. RV Transmitter Power and Antenna Gain

A power output of 6.5 W (8.13 dBW) was employed in this study for the Trident MK-4 transmitters, and 4 W (6 dBW) was employed for the MX MK-12 transmitters, based on SSTSS Navy and Air Force requirements for Trident and MX support in the broad ocean area. Graphs of 95 percentile antenna gain vs aspect angle (measured from the RV nose) for the MK-4 and MK-12 with combined right- and left-hand circular polarization, are taken from the APATS specification, and are plotted in Figure 9. As the RVs rotate, the antenna gain exceeds the value in the graph 95% of the time. Formulated empirical approximations to these curves were used in the analysis so that gain values could be computed readily as functions of the aspect angle ϕ. For the MK-4, this empirical gain, in dB, is

$$G_4 = -4 - \phi/6 - 15\ e^{-0.5\ \phi} \quad . \qquad (3)$$

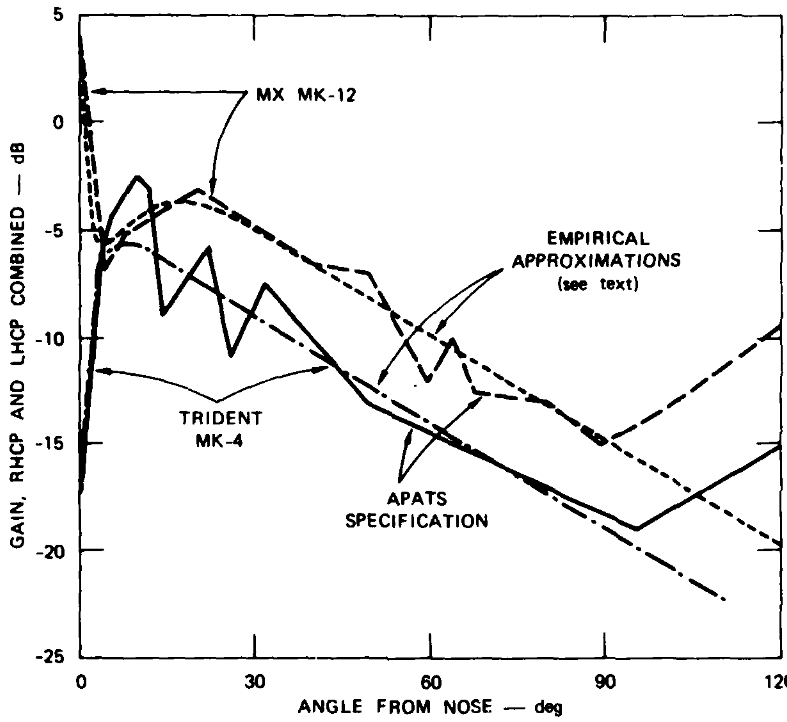


FIGURE 9 RV ANTENNA GAIN (from APATS specification) AND EMPIRICAL APPROXIMATIONS EMPLOYED TO COMPUTE GAIN AS A FUNCTION OF ASPECT ANGLE

For the MK-12, the empirical gain, in dB, is

$$G_{12} = -\phi/6 + 24\ e^{-0.4\ \phi} - 20\ e^{-0.18\ \phi} \quad . \qquad (4)$$

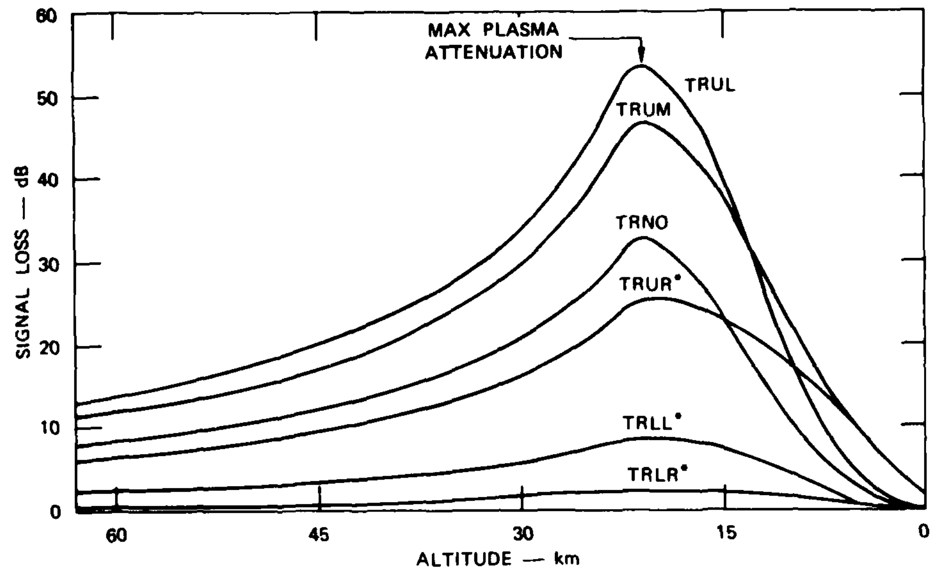
In general, G_{12} is about 4 dB larger than G_4, although in the nose direction the difference increases to 23 dB, and between $\phi = 5^o$ and $\phi = 9^o$ it decreases to less than 1 dB. The approximations are not good beyond $\phi = 100^o$, but only a few points in the following examples go beyond that value, and these are near RV impact, where the signal is strong and the error is conservative. The maximum value of ϕ occurs at impact point 3, where its value is about 106^o.

A potential problem exists in using 95-percentile transmitting antenna gain curves to design a telemetry receiving antenna system to receive signals from the transmitting antenna in question. Once the receiving antenna system has been designed, complete information on the gain and polarization pattern of the transmitting antenna gain must be supplied to the designer of the telemetry system to allow him to strike a balance among transmitter power, polarization and/or frequency diversity or combining schemes, modulation design, and error correction design. The RV rotation rate must be taken into account, because the frequency spectrum of the gain variation will contain the rotation rate and its harmonics. The depth and durations of the nulls will be of paramount importance. For example, in one set of transmitting antenna pattern data developed by Lockheed and reviewed by SRI for this study, in which LHCP and RHCP were combined for the highest level, the depths of the nulls varied from 10 to 30 dB, depending on the nose aspect angle, and the nulls were from 2 to 10 dB below the 95-percentile level. The difference between the 95-percentile level and the null (100-percentile) level must somehow be taken into account in the telemetry system design, especially in cases in which no recording and playback capability are provided and in which a 13 dB SNR is required 100% of the time. Such system design details are beyond the scope of this study. Since 95-percentile levels are used in the APATS specification, it is assumed here that the telemetry community is prepared to operate on that basis, with the understanding that the SNR will drop below 13 dB temporarily during the passage of each null since no margin has been allowed.

C. Plasma Attenuation

Figures 10 and 11 are working-value signal-loss curves adapted from the APATS specification. The loss, due principally to plasma attenuation, is expressed in decibels as a function of altitude. Each curve corresponds to a different trajectory type, which could be characterized by a point on a v-gamma plot, although this was not done in the APATS specification. The curves that are used in the following examples are the TRUL, TRUM, and TRNO MK-4 curves and the Case 2 and Case 3 MK-12 curves.

For received signal strength computation purposes in a particular geometry, it is necessary to know the RV reentry angle. Since reentry angles for the different trajectories were not given in the APATS



*Not used in present study.

FIGURE 10 MK-4 LOSS CURVES (from APATS specification)

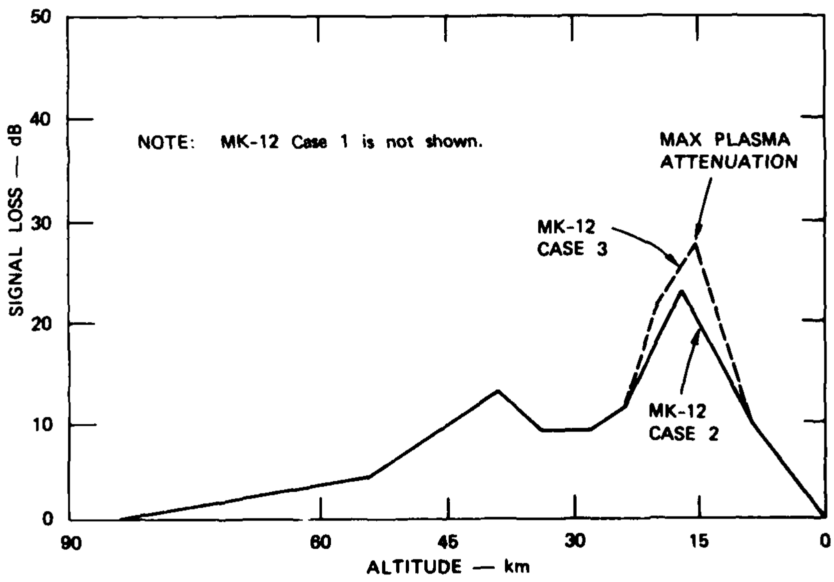


FIGURE 11 MK-12 LOSS CURVES (from APATS specification)

specification, certain working values were assumed and are summarized in Table 5. Since the aspect angles and distances are not highly sensitive to the reentry angle, the fact that true values were not available (and therefore not employed) should not affect a parametric study significantly.

Table 5

ASSUMED WORKING VALUES FOR REENTRY ANGLES

RV	TRIDENT MK-4			MX MK-12	
Trajectory	TRUL*	TRUM*	TRNO*	Case 2	Case 3
Estimated Reentry Angle	25°	40°	25°	28°	25°

*Positions of reentry conditions on a v-γ plot (e.g. UL = upper left, UM = upper middle, NO = nominal).

D. Field Strength Contours

Figures 12 and 13 illustrate the computed field strength of the MK-4 TRNO and MK-12 Case 2 RVs at an RV altitude of 15 km and an aircraft altitude of 3 km, as functions of the XY position of the aircraft. At this altitude, both RV types have passed the point of greatest plasma attenuation and the strengths of the signals received by the aircraft are beginning to increase rapidly. X and Y are measured from impact, with X east and Y north. The XY positions of the impact point and of the RV at 15-km altitude are both shown as small crosses. The RV approaches from the east at the appropriate elevation angle (see Table 5 in Section IV-A). The loss at 15 km altitude is about 22 dB for both RV trajectories. The earth is assumed to be flat. The plotted field strength is expressed in dBW/m^2, and the particular value of -129.2 corresponding to the APATS specification is shown as an oval dotted curve.

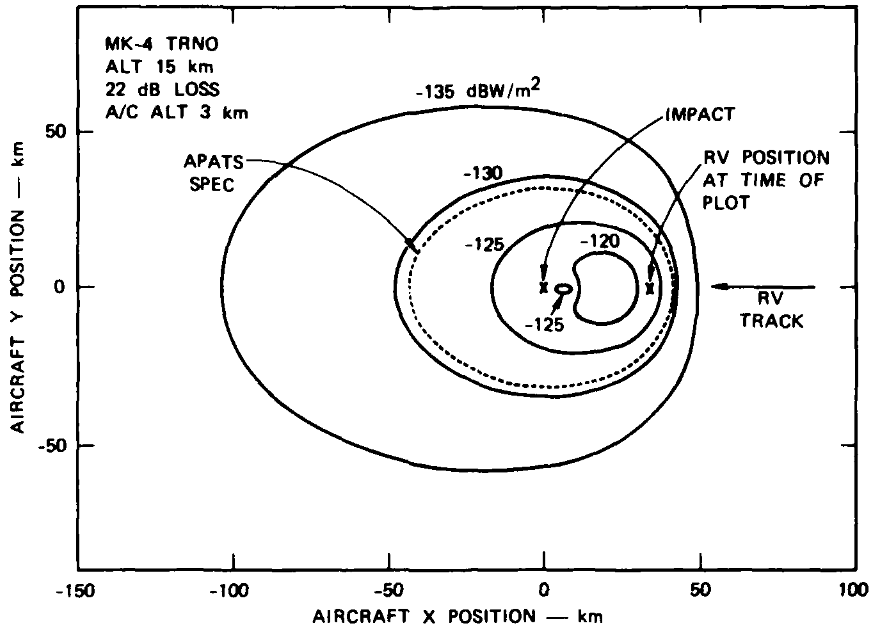


FIGURE 12 MK-4 TRNO POWER DENSITY CONTOURS AT 15-km ALTITUDE

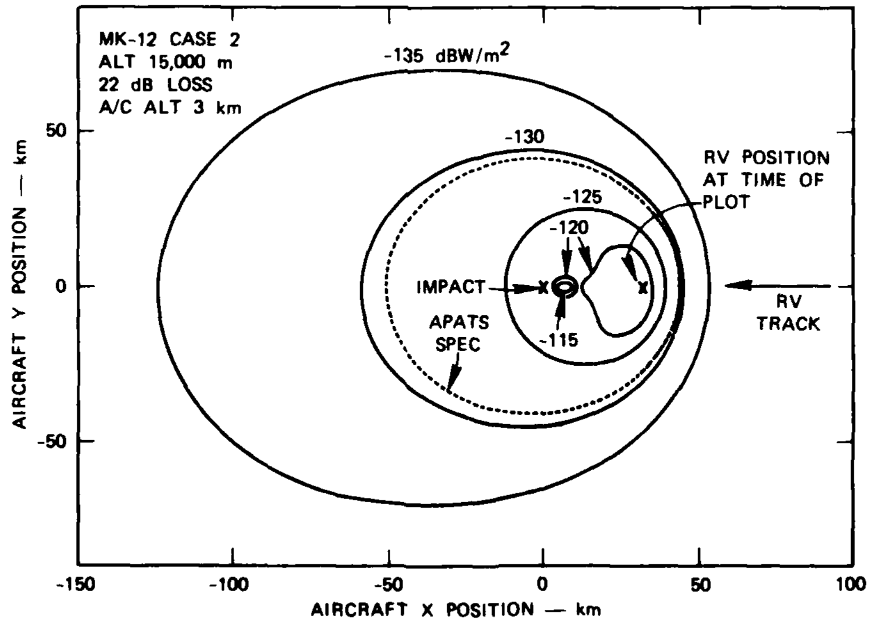


FIGURE 13 MK-12 CASE 2 POWER DENSITY CONTOURS AT 15-km ALTITUDE

The equations used for computing the field strength are given in Appendix A.

If the airborne telemetry antenna does not exceed the APATS sensitivity specification, the aircraft must be placed inside the oval dotted curve, in order to receive telemetry from an RV at 15-km altitude with a SNR of 20 (13 dB) or more. The value of X for which the permissible Y standoff is greatest is seen to be somewhere near zero. The permissible standoff is seen to be about 33 km (18 nmi) for the MK-4 TRNO and about 40 km (22 nmi) for the MK-12 Case 2.

This method of presentation can be adapted to studies of area coverage for multiple RV impacts in various patterns and spacings by superimposing several of the dotted oval curves on a single drawing. The area common to all of the oval enclosures simultaneously is then the only area within which signals can be received simultaneously from the several RVs at the given altitude. An example is shown in Figure 14 for three MK-12 in-line impacts 30-km (16 nmi) apart. The area common to the three oval curves is shaded. The maximum standoff distance for adequate signal strength in this example is seen to be about 32 km (17 nmi). An additional example, for a fan type of deployment, is shown in Figure 15. In this example, the best aircraft support position

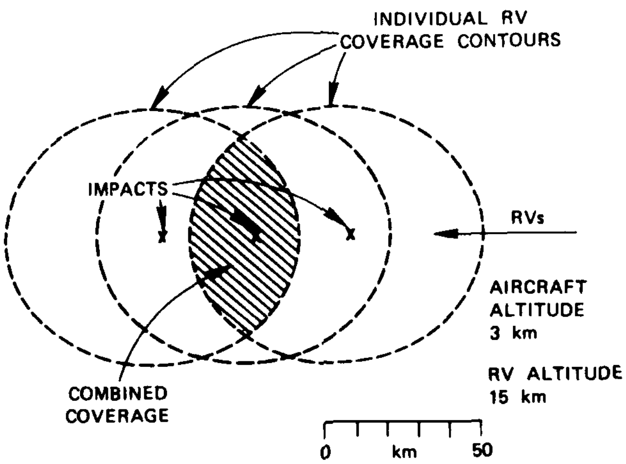


FIGURE 14 MK-12 CASE 2 IN-LINE FOOTPRINT

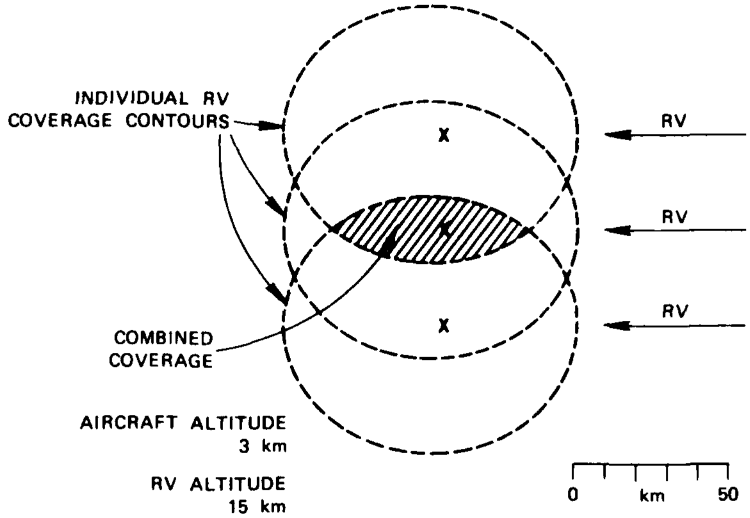


FIGURE 15 MK-12 CASE 2 FAN-PATTERN FOOTPRINT

seems to be about 35 km downrange from the middle RV impact point; however, this downrange aircraft position is not permitted by safety considerations. Fortunately, current MX and Trident planning will target all RVs into a 12- to-14 nmi diameter SMILS pattern so that neither fan-type nor in-line impacts will have to be accomodated.

IV ANALYSIS OF TELEMETRY RECEPTION WITH EATS AND APATS ANTENNAS

A. Performance of As-Proposed EATS and APATS Antennas

Figures 16 through 24 are graphs of computed SNRs versus RV altitude and corresponding angular directions of signal arrival at the aircraft antenna for several different combinations of RVs, trajectories, and antenna types. As stated previously, the transmitter power is taken as 6.5 W for MK-4 RVs and 4 W for MK-12 RVs. The impact points are identified by number as in Figure 7, which also shows the aircraft standoff position, which is compatible with range safety restrictions. In all cases, the aircraft altitude is 3000 m. In each case, the aircraft heading is such that the antenna boresight azimuth is toward the trajectory point of the RV producing the weakest signal, at the time (altitude) the signal is weakest. This heading is assumed to remain fixed. The RV antenna gain values employed in the computations are empirical approximations defined by Eqs. (3) and (4) and illustrated in Figure 9. Reentry losses are read from the graphs in Figures 10 and 11. Assumed values of reentry angles are listed in Table 5. The total noise temperature is taken to be 415 K plus the background temperature, which varies with the beam elevation angle. For most of the elevation range, the background temperature is less than 15 K, and has little effect on the results, but it becomes more important as the beam drops below horizontal where the temperature increases to 290 K. The computed SNRs correspond to a bandwidth of 1.5 MHz. The computation procedure is described in Appendix A.

Figure 16 is a graph of the SNR as a function of RV altitude for a MK-4 TRUL* trajectory impacting at point 1, for three different antenna configurations: Mod-1, with the aircraft in level flight, Mod-1 with the aircraft banked 20°, and Mod-2 in level flight. Blackout is defined arbitrarily as any condition in which the SNR falls below 13 dB. It can

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*Position of reentry conditions on a v-γ; UL = upper left.

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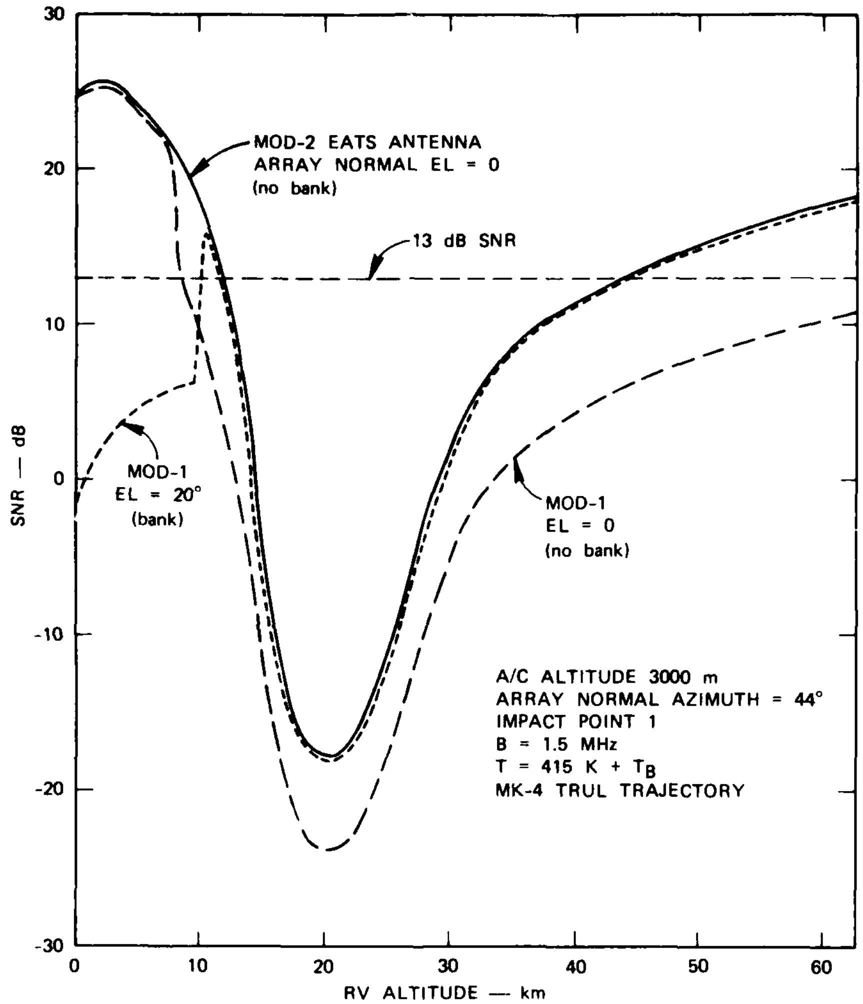

FIGURE 16 MOD-1/MOD-2 EATS SIGNAL-TO-NOISE RATIO (SNR) COMPARISON FOR MK-4 TRUL TRAJECTORY, SHOWING THE EFFECT OF BANKING THE AIRCRAFT 20° IN THE MOD-1 CASE

be seen that the blackout altitude range extends from about 43 to 12 km for the Mod-2 antenna. The Mod-1 banked case has the same blackout range as the Mod-2 antenna and also loses the required 13 dB SNR below 10 km, because the last part of the trajectory is below the elevation scan limit of the antenna when the aircraft is banked. If the aircraft could remain banked until the RV reaches 12 km and then rotate quickly into level flight, the signal would not be lost during the last part of the trajectory, and the blackout limits would then be esentially the same as those of the Mod-2 antenna. However, this technique requires critical maneuver timing and may be impracticable if two or more RVs arrive at once.

Figure 17 is similar to Figure 16, except that the RV is a MK-12 Case 2 impacting at point 4, and the aircraft is banked 15° rather than

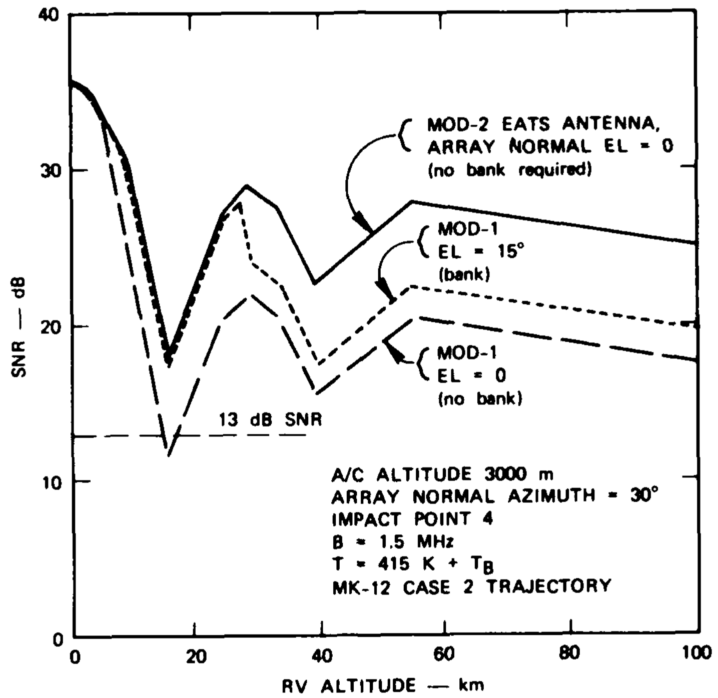

FIGURE 17 MOD-1/MOD-2 EATS SNR COMPARISON FOR MK-12 CASE 2 TRAJECTORY, SHOWING THE EFFECT OF BANKING THE AIRCRAFT 15° IN THE MOD-1 CASE

20°, because maximum loss for the MK-12 occurs at a lower altitude than for the MK-4 TRUL. It can be seen that the Mod-1 antenna, without banking, suffers temporary blackout when the RV altitude is near 16 km, while banking the aircraft 15° permits blackout to be avoided. In a multiple RV exercise, in which banking the aircraft might be impracticable, it would be necessary to employ the Mod-2 antenna to avoid blackout. However, Case 3 with the MK-12 will be shown later to be the stressing case.

In Figure 18 the EATS Mod-2 and the APATS equivalent (Mod-3) antenna results are compared for the situation in which four MK-4 RVs arrive at

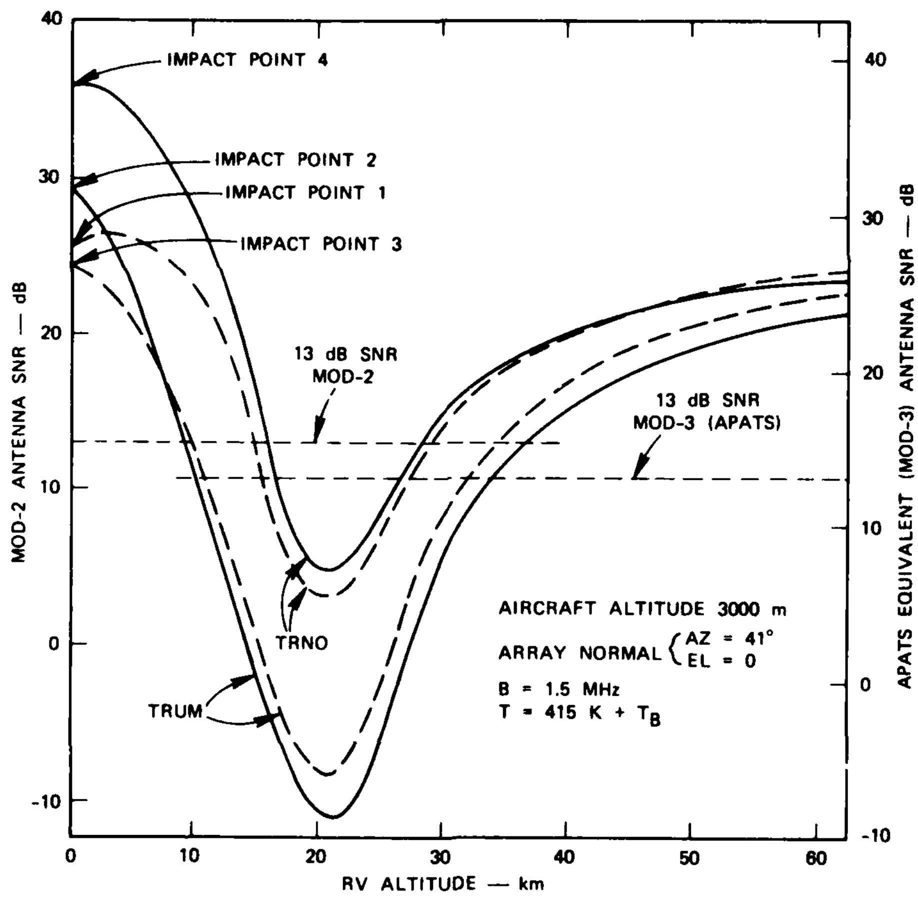

FIGURE 18 EATS/APATS SNR COMPARISON FOR TWO MK-4 TRUM AND TWO MK-4 TRNO TRAJECTORIES

approximately the same time. Two of the RVs are on TRNO trajectories impacting at points 1 and 4, while the other two are on TRUM trajectories impacting at points 2 and 3. The aircraft is in level flight and is headed in a direction such that the array boresight points toward 41° azimuth, which is the direction of the maximum loss point on the TRUM trajectory impacting at Point 2. The SNR scale for the Mod-2 antenna is on the left side of the graph, while that for the Mod-3 is on the right, and the 13-dB levels are indicated separately by horizontal broken lines. All of the RVs suffer marked blackouts. All of the curves are rather steep at the 13-dB levels, which means that the blackout in the Mod-3 case is of only slightly shorter duration than in the Mod-2 case. Curves of elevation vs azimuth (relative to the array) are shown in Figure 19, with the blackout limits for Mod-2 and APATS equivalent (Mod-3) antennas indicated. Figures 20a and 20b are estimates of the relative wing and tail positions in the angular FOVs on 707 and P-3 type aircraft. Potential blockage would be minimized when the 707 or EC135N type aircraft heads downrange, and when the EATs P-3 type aircraft heads uprange.

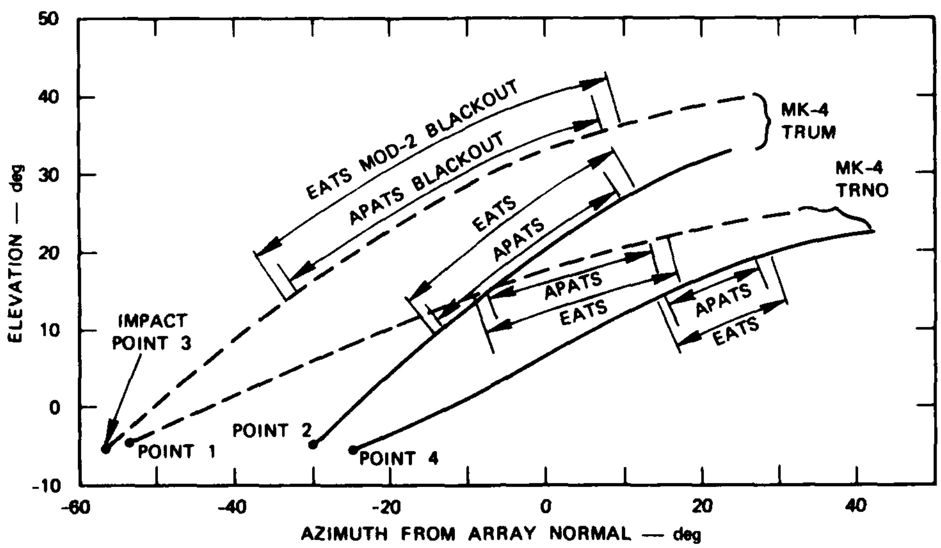

FIGURE 19 EATS/APATS BLACKOUT COMPARISON FOR TWO MK-4 TRUM AND TWO MK-4 TRNO TRAJECTORIES

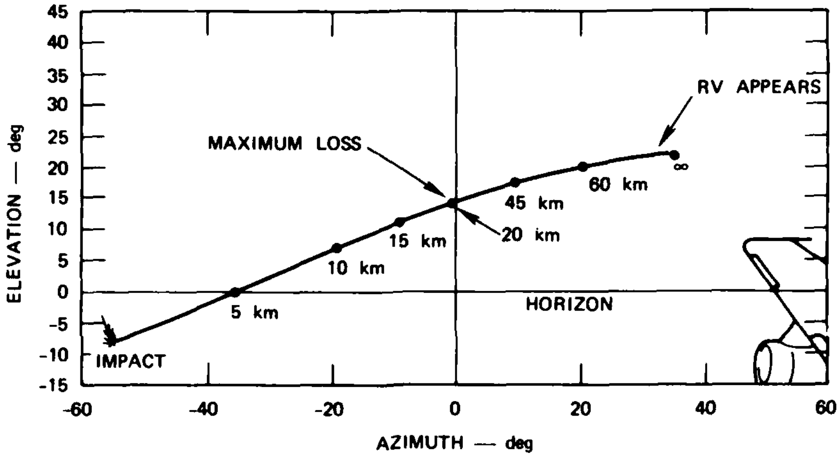

FIGURE 20a APATS ANTENNA STARBOARD SIDE FOV BLOCKAGE ESTIMATE (mounted forward of wing on 707-type aircraft)

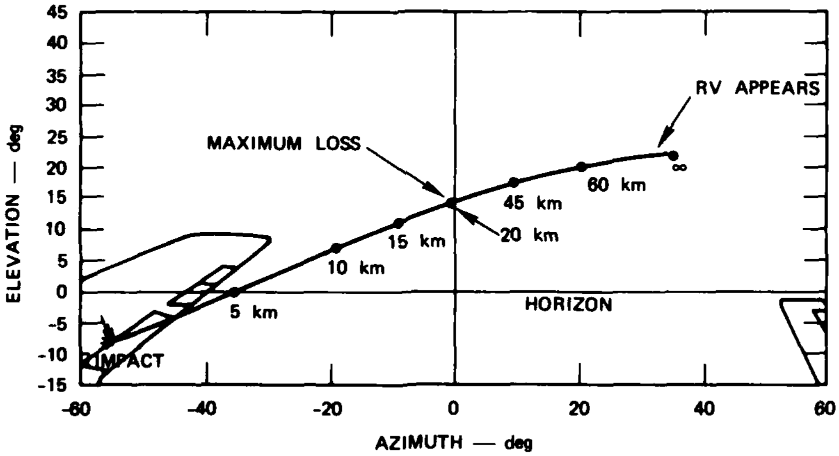

FIGURE 20b EATS ANTENNA STARBOARD SIDE FOV BLOCKAGE ESTIMATE (mounted forward of tail on P-3 aircraft)

Figure 21 compares the performance of the Mod-2 and APATS equivalent (Mod-3) antennas when receiving signals from two MK-4 RVs on TRUL trajectories impacting at points 1 and 4. There is a noticeable difference in the altitudes at which blackout begins, about 42 km for the Mod-2 and about 36 km for the Mod-3, but not much difference between the altitudes (12 to 13 km) at which blackout ends. At maximum loss, the SNR falls to -15 dB or lower. The curves of elevation vs azimuth (relative to array normal) are plotted in Figure 22.

As noted previously, the MK-4 RVs have the capability of recording data during blackout and for replay and delayed transmission after blackout. Thus, the importance of avoiding telemetry blackout is not as critical for this Navy RV as it is for the Air Force MK-12. Figures 18 through 22 demonstrate that the altitude at which blackout ends is only 5% or 10% greater for the APATS equivalent antenna than for the EATS Mod-2 antenna. Since the RVs are decelerating at this time, due to drag, the incremental time fraction remaining for transmission in the APATS case, compared with the EATS Mod-2 case, is even smaller than the incremental altitude fraction would indicate. For these reasons, the APATS antenna does not appear to offer a great advantage over the EATS Mod-2 antenna in MK-4 applications.

Figure 23 compares the performance of the EATS Mod-2 and APATS equivalent (Mod-3) antennas when receiving signals from two MK-12 Case-2 RVs impacting at points 1 and 4. It can be seen that the SNR remains well above the 13 dB level for both antennas. Figure 24 compares the same antennas when receiving signals from two MK-12 Case-3 RVs, also impacting at points 1 and 4. It can be seen that the SNR in the Mod-2 antenna falls below 13 dB for both RVs, and that even the APATS equivalent (Mod-3) antenna is marginal for one of the RVs.

A -13 dB SNR reference has been added to both Figures 23 and 24 to represent the case of the original ARIA dish antenna at the same support position, for comparison. (Instead of being a straight horizontal line, it droops slightly on both sides because, unlike the arrays, the dish antenna maintains constant gain as it scans.) The G/T of the dish is

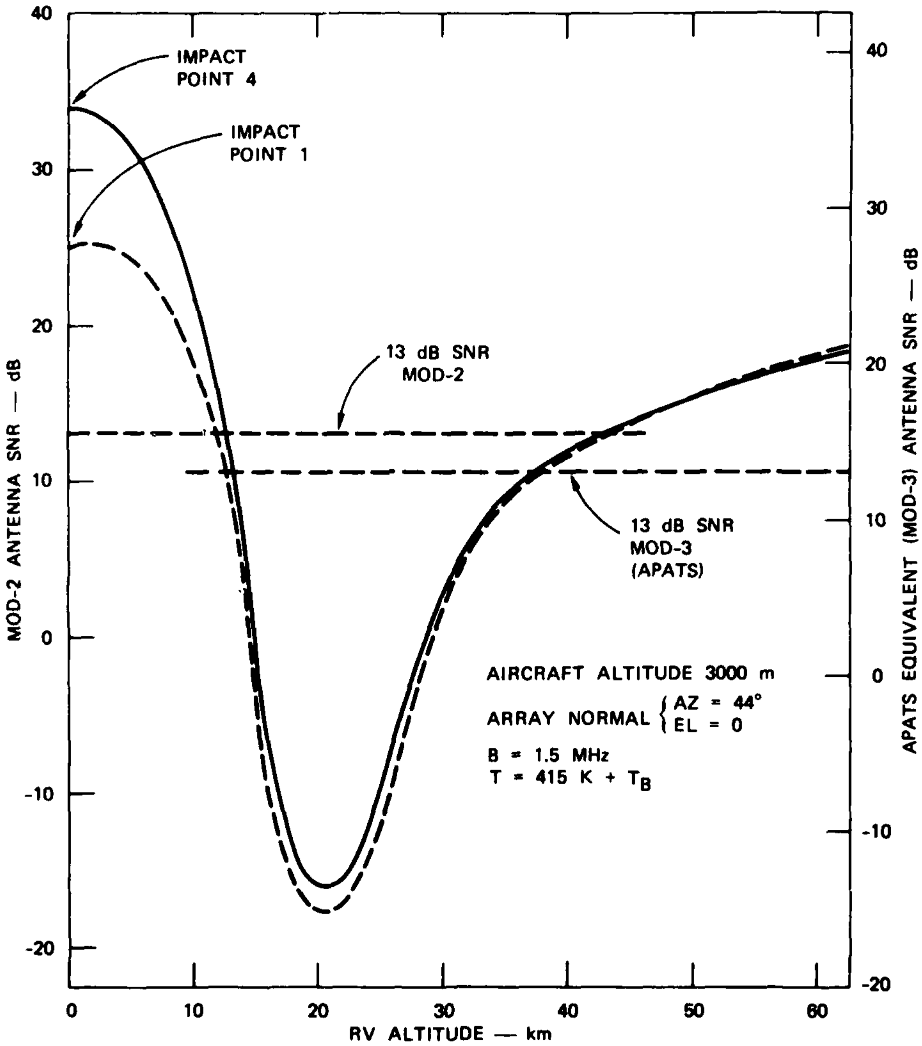

FIGURE 21 EATS/APATS SNR COMPARISON FOR MK-4 TRUL TRAJECTORY

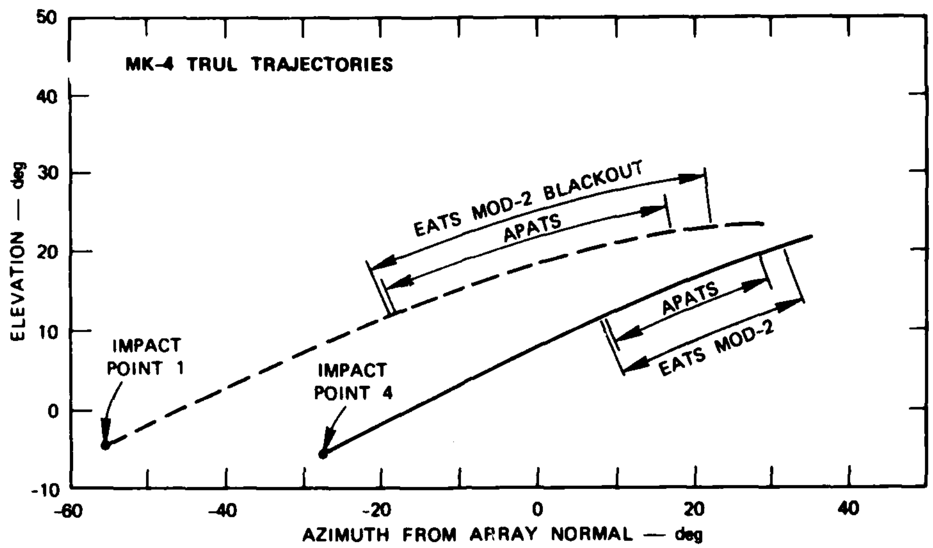

FIGURE 22 EATS/APATS BLACKOUT COMPARISON FOR TWO MK-4 TRUL TRAJECTORIES

taken to be 3.7 dB/K, which places the peak of the curve 3.2 dB above the Mod-2 13-dB line and 4.9 dB above the APATS equivalent (Mod-3) 13-dB line. In actual practice, the ARIA with the nosedish would be in a more downrange support position, rather than off to one side.

Figure 24 indicates that some operating scenarios exist in which the APATS antenna cannot provide MK-12 telemetry 100% of the time with a SNR of 13-dB. Possibly this problem could be solved by decreasing the stand-off requirements, so that the aircraft support position could be moved closer to the impact points at the expense of increasing the angular coverage requirement. However, the analyst is still faced with the problem of a system design based on a 95-percentile RV antenna gain curve, rather than a 100-percentile curve. Although this problem was not treated in this study, the comments contained in Section II-B on RV transmitter power and antenna gain are applicable. Also, it should be noted that the computations on which Figures 16 through 24 are based do not allow any margin for losses due to factors such as weather, multipath interference, equipment aging, or antenna pointing errors.

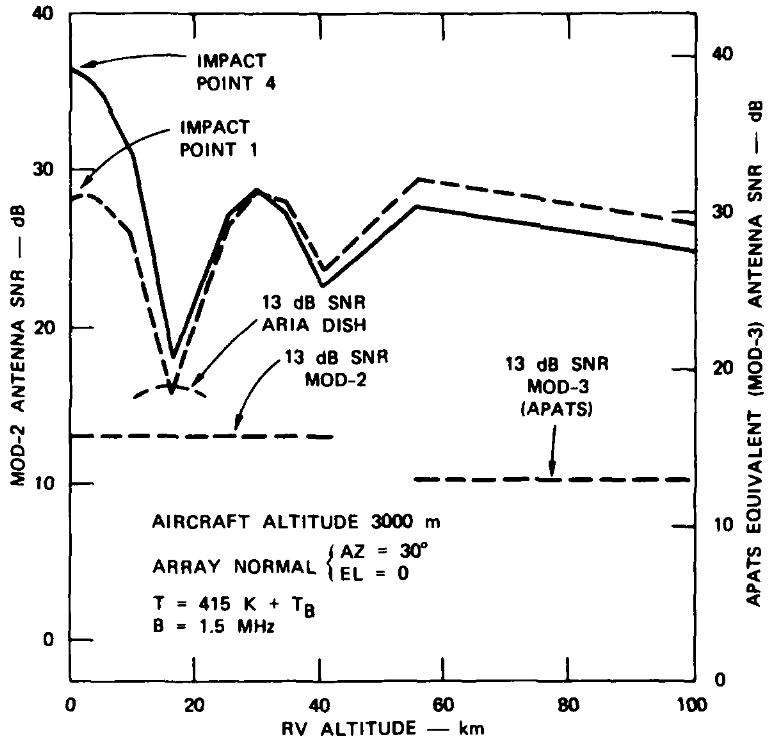

FIGURE 23 SNR AS A FUNCTION OF RV ALTITUDE FOR MK-12 CASE 2 TRAJECTORY

B. Theoretical Elevation/Gain Profile Requirements

So far, this report has been concerned with the ability of different antennas to receive RV signals in representative scenarios, and it has been shown they are likely to be successful only part of the time. In contrast, the following discussion concerns the value of the figure of merit, G/T, that would be necessary to realize RV signal reception 100% of the time, while keeping the same reservations that 95-percentile transmitting antenna patterns will be acceptable, no loss margins will be included, and no correction will be included for aircraft roll instability (e.g., ~ 5° to 10°).

Figure 25 shows the computed value of the required figure of merit, G/T, expressed in dB/K, for the more stressing of the trajectories analyzed previously, plotted as functions of the elevation scan angle. The effects

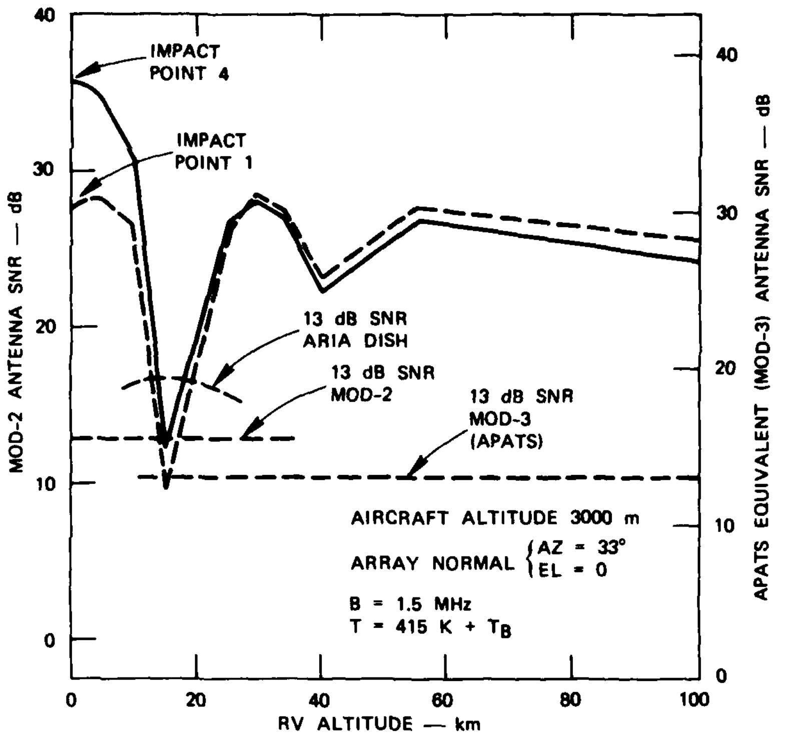

FIGURE 24 SNR AS A FUNCTION OF RV ALTITUDE FOR MK-12 CASE 3 TRAJECTORY

of azimuth scan have been ignored for simplicity. As a reference, the value of G/T provided by the APATS equivalent antenna has been plotted as a dotted curve.

It can be seen that the APATS provides a sufficient value of G/T only at elevation angles above 35° and below 8° for the range of trajectory types considered here. These angles change to 40° and 3° if a plus or minus 5° allowance is added for aircraft roll. The highest required G/T evidently is about 38 dB/K. For an antenna of the EATS type, with a system temperature of 415 K and an aperture efficiency of 0.4, this would require a physical array area of about 9,000 m^2, which is entirely impractical. Some compromise therefore is necessary between the fraction of time successful telemetry reception will be required and the cost and weight of the antenna. The APATS specification represents such a compromise, although it is possible to question whether it is the best compromise that could have been made.

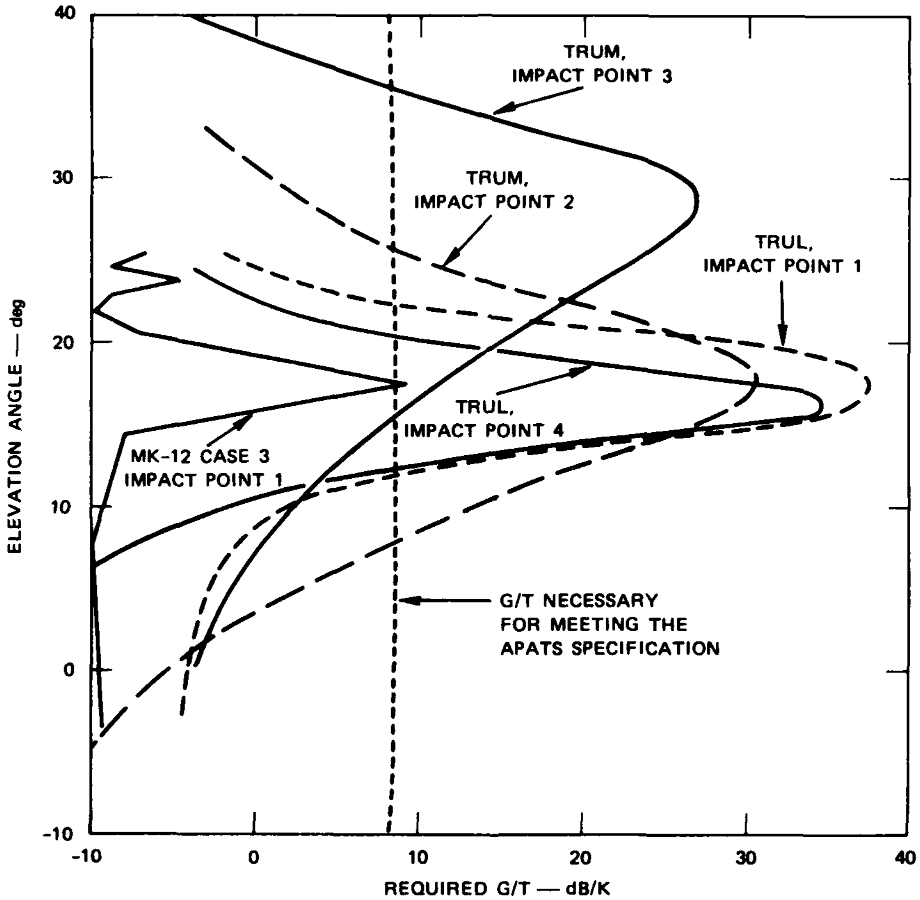

FIGURE 25 VALUE OF G/T NECESSARY TO AVOID BLACKOUT FOR SELECTED RV CASES

APPENDIX

COMPUTATION OF SIGNAL-TO-NOISE RATIO

The RV is assumed to follow a straight line to the impact point, making an angle, γ, with the horizontal. The earth is assumed to be flat in the local region. A right-handed xyz coordinate system is employed, with x east, y north, and z up, and with the impact point located at the origin. The RV path is assumed to lie in the xz plane, with the RV moving from east to west. The geometrical relationships are illustrated in perspective in Figure A-1. The following terms are defined:

h = RV altitude, m
b = RV slant range from impact, m
γ = reentry elevation angle
x, y, z = aircraft coordinates, m
r = slant distance from aircraft to RV, m
d = slant distance from aircraft to impact point, m
ϕ = RV nose aspect angle (angle between b and r)
E = elevation angle of RV, viewed from aircraft
E_b = elevation angle of aircraft antenna boresight
A = azimuth angle of RV, viewed from aircraft (measured from north toward east)
A_b = azimuth angle of aircraft antenna boresight
D_p = radiation power density of signal arriving at aircraft, W/m^2
P_t = RV transmitter output power, W
G_t = RV antenna gain in direction of aircraft, numeric
L = atmospheric loss (primarily plasma loss), numeric
A_n = normal (boresight) aperture of aircraft antenna, m^2
T = temperature, K
k = 1.38×10^{-23} J/K
B = bandwidth, Hz.

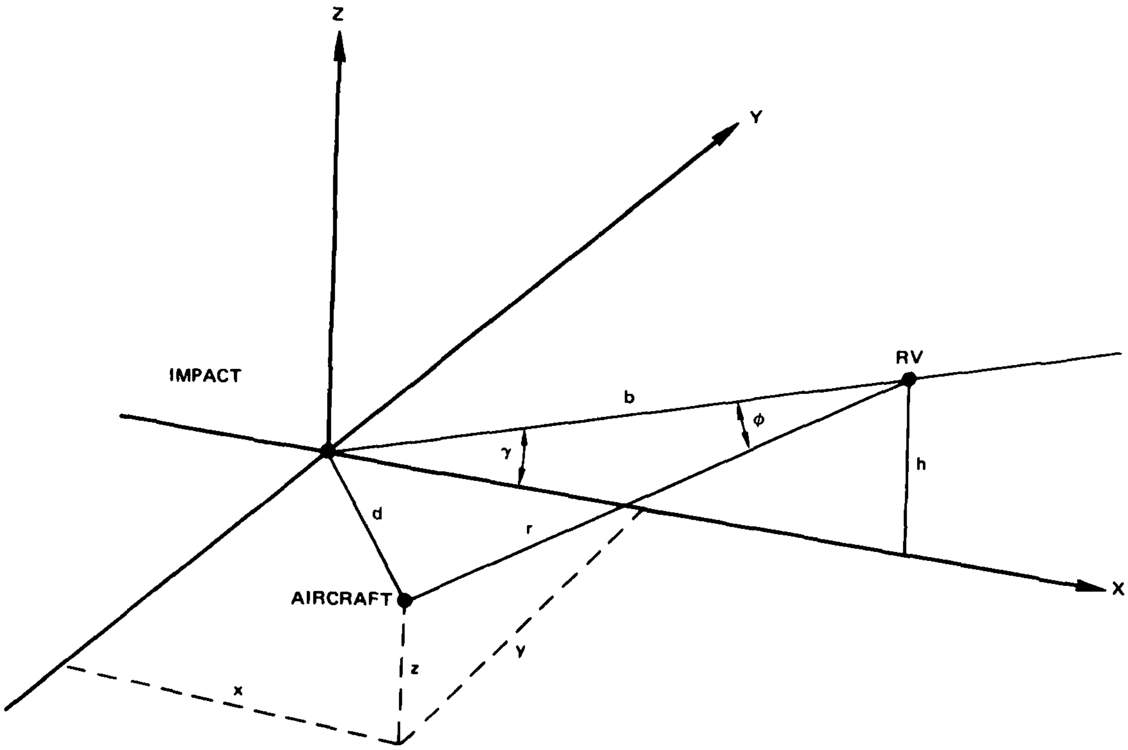

FIGURE A-1 GEOMETRY DETERMINING b, r, d, AND ϕ

The following series of equations leads progressively to a solution for the SNR, R_{sn}:

$$b = h / \sin \gamma \quad . \tag{A-1}$$

$$r^2 = (b \cos \gamma - x)^2 + y^2 + (h - z)^2 \quad . \tag{A-2}$$

$$d^2 = x^2 + y^2 + z^2 \quad . \tag{A-3}$$

$$\phi = \arccos \frac{b^2 + r^2 - d^2}{2br} \tag{A-4}$$

$$E = \arcsin \frac{h - z}{r} \quad . \tag{A-5}$$

$$A = \text{polar angle of } -y, (b \cos \gamma - x) \quad . \tag{A-6}$$

$$D_p = P_t G_t / 4\pi r^2 L \quad . \tag{A-7}$$

$$R_{sn} = \frac{D_p A_n [\cos (E - E_b)]^{1.25} \cos [(A - A_b)]^{1.25}}{kTB} \quad . \tag{A-8}$$

The altitude, h, in Eq. (A-1) is the independent variable. The angle γ is obtained from Table 5. The aircraft coordinates x and y in Eqs. (A-2) and (A-3) are derived from Figure 7, the origin of the coordinate system being moved from one impact point to another as different RV trajectories are examined. The aircraft altitude, z, in this study was taken as 3,000 m (3 km). The value of P_t in Eq. (A-7) is taken as 6.5 W for MK-4 RVs or 4 W for MK-12 RVs. The value of G_t is given by Eq. 3 (see text) for MK-4 RVs or by Eq. 4 for MK-12 RVs. The value of the loss, L, read in dB from either Figure 10 or Figure 11, is converted to a numeric for use in Eq. (A-7). The value of A_b in Eq. (A-8) is determined as described in Section IV-A of the text. The value of E_b is taken as zero for the Mod-2 antenna or 15^o for the Mod-3 antenna. For the Mod-1 antenna it is equal to the angle of bank of the aircraft. The value of B is taken as 1.5×10^6 Hz (1.5 MHz).

The value of the temperature, T, in the denominator of Eq. (A-8) is the sum of 415 K and the temperature T_b read from the graph in Figure A-2. This value of T_b is an estimate, since the beamwidth and sidelobe levels of the antenna are not known precisely. Because it is added to 415 K, its effect is unimportant when it is small, as is the case at the higher elevation angles where signal margin may be a problem. At lower elevation angles, where T_b is larger, any resulting error is of less importance, because the signal margin is larger.

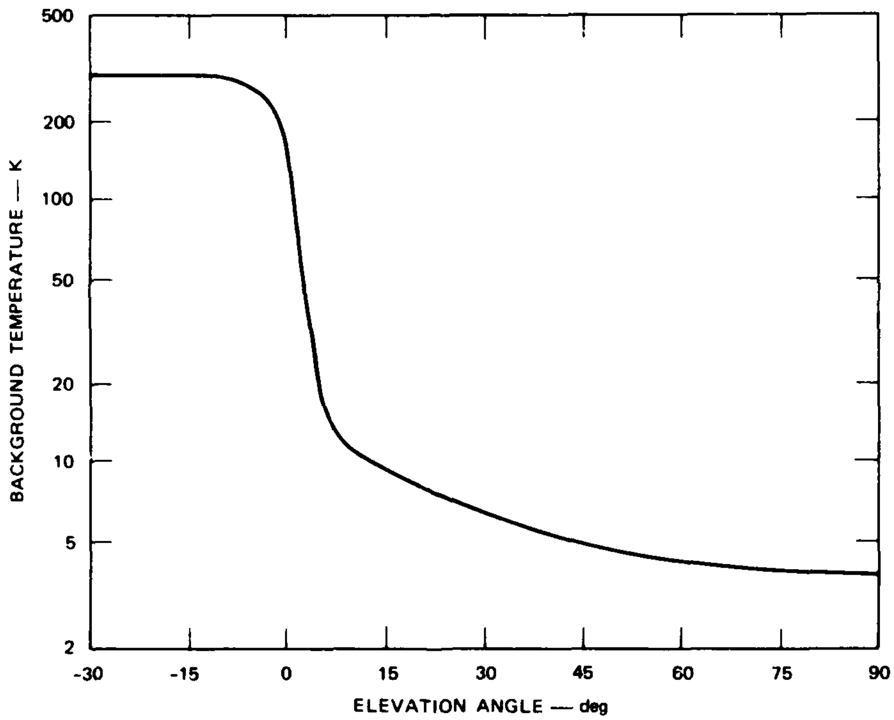

FIGURE A-2 BACKGROUND TEMPERATURE (estimated) AS A FUNCTION OF ELEVATION ANGLE

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